Available online at www.sciencedirect.com
SCIENCE DIRECT®
Nuclear Engineering and Design 222 (2003) 161–171
Nuclear Engineering and Design
www.elsevier.com/locate/nucengdes

Neutronic features of the GT-MHR reactor

N. Kodochigov [a,*], Yu. Sukharev [a], E. Marova [a], N. Ponomarev-Stepnoy [b], E. Glushkov [b], P. Fomichenko [b]

[a] *OKB Mechanical Engineering, Nizhny Novgorod, 15 Burnakovsky proezd 603074, Russia*
[b] *RRC Kurchatov Institute, Moscow, Russia*

Received 14 March 2002; received in revised form 15 October 2002; accepted 20 December 2002

Abstract

The design of a Gas Turbine–Modular Helium Reactor (GT-MHR) of 600 MWt power is being developed in frames of “The Agreement between the Government of the United States of America and the Government of the Russian Federation on Scientific and Technical Cooperation in the Management of Plutonium That Has Been Withdrawn from Nuclear Military Programs” signed on July 24, 1998. The reactor concept is based on the deep burnup of initially loaded plutonium fuel at its single use in core and the subsequent disposal of the spent fuel without additional processing.

The present paper describes the analysis of the basic features of the GT-MHR reactor core fueled by plutonium:

1. The annular type core design is used to decrease fuel temperature in accidents without active heat removal.
2. Unlike other alternatives for plutonium disposition (MOX fuel), in the basic variant of GT-MHR reactor design no fertile materials such as U-238, or Th-232 are used. Erbium is used as a burnable poison and means for ensuring the negative reactivity temperature coefficient.
3. Deep fuel burnup (640 MW day/kg on the average) leads to the significant accumulation of Pu-241 during irradiation of weapons grade Pu fuel. This fact determines the specific time dependence of the multiplication factor in the end of the fuel lifetime.
4. Rather hard neutron spectrum in the annular-type active core, and the essentially thermal spectrum in the reflectors cause a peak in the power distribution near the core-reflector boundary. Fuel and burnable poison zoning are used to control power profile.
5. The movement of control rods located in the side reflector noticeably deforms the power distribution in the core.
6. The temperature coefficient of reactivity depends both on the temperature and burnup level. In the GT-MHR reactor with plutonium fuel the temperature reactivity coefficient has values close to zero for temperatures less than 400 °C at the end of the partial fuel cycle.
7. Deep fuel burnup, achievable through the use of fuel particles with multilayer coatings, and high efficiency of transforming the thermal energy into electricity allow the effective utilization of plutonium in the GT-MHR reactor.

1. Introduction

Large amounts of weapons grade plutonium (WGPu) have been currently accumulated in the world. These stockpiles of accumulated plutonium are potentially hazardous because of possibility of

* Corresponding author. Tel.: +7-8312-462132; fax: +7-8312-418772.
E-mail address: marova@okbm.nnov.ru (N. Kodochigov).

0029-5493/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0029-5493(03)00010-4

their proliferation with the subsequent manufacture and use of nuclear weapons. From this point of view, the problem of the plutonium disposition is urgent.

On the other hand, plutonium is an extremely valuable source of energy, so it has to be efficiently used. The idea of WGPu burning in nuclear power plants to ensure electricity production is the official Russian position (Ponomarev-Stepnoy, 2000). WGPu burning in reactors is considered as a long-term problem connected with the modification of existing power plants as well as with the development of new reactor technologies.

Along with operating VVER-1000 and BN-600 reactors, the high temperature reactor with gas turbine GT-MHR (Kiryushin and Ponomarev-Stepnoy, 1997) of 600 MWt power is considered in the Russian Federation as a candidate reactor for additional WGPu disposition because of very high resistant ability of fuel on the basis of coated particle to retain the fission products at high burnup, these reactors capability to reach more deep level of initial Pu-239 destruction as compared with other type reactors (VVER, BN) and use the energy potential of WGPu most completely. The GT-MHR is being developed under the international cooperative program involving institutions of the Russian Federation Ministry of Atomic Energy, Russian Research Center "Kurchatov Institute", foreign companies and laboratories: General Atomics, ORNL, LANL (USA), Framatome ANP (France), Fuji Electric (Japan). The overall goals of the cooperative program are initially to develop the GT-MHR for the disposition of surplus weapons plutonium in Russia, and then to offer GT-MHR plants fueled by uranium to the international market for the electricity generation.

2. Conception of WGPu use in the GT-MHR reactor

The idea of WGPu disposition in the GT-MHR (Kiryushin and Ponomarev-Stepnoy, 1998) is based on the high burnup of initially loaded Pu at its single use in core and the subsequent storage of spent fuel in multi purpose canister in the final disposal facility without processing.

The general scheme of WGPu disposition is shown in Fig. 1.

Plutonium fuel in the reactor is used in the form of fuel particles with multilayer coatings. Plutonium oxide spheres of 200 μm diameter are coated firstly by low-density pyrocarbon, then by high-density pyrocarbon and silicon carbide (TRISO-coated

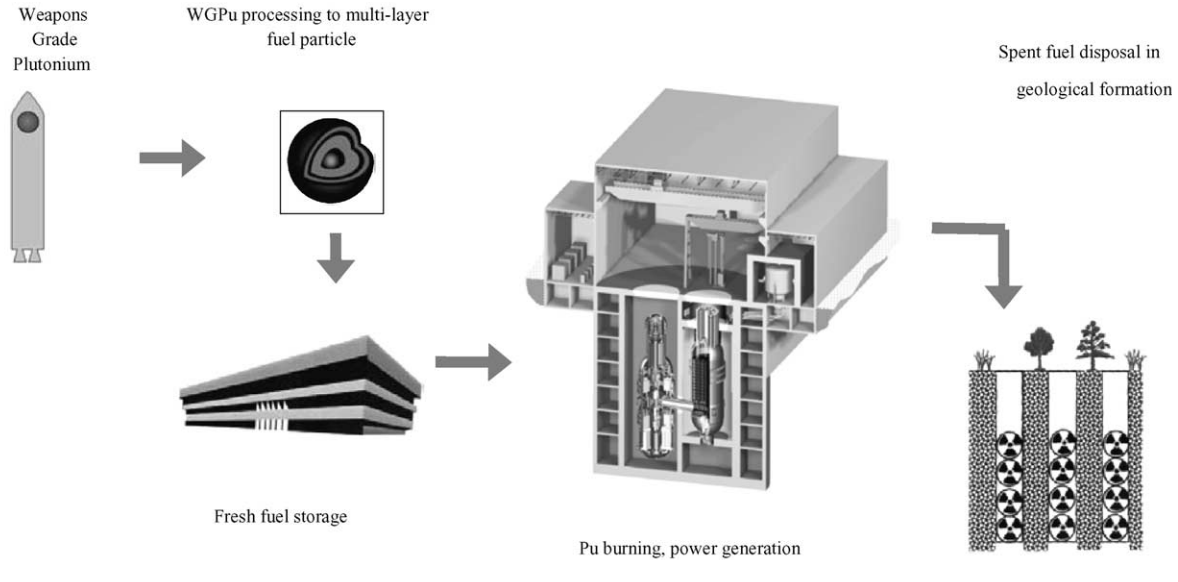

Fig. 1. WGPu utilization scheme.

particles). The outside diameter of particles is about 620 μm. The coated fuel particles are bonded together with carbonaceous matrix into rod-shaped compacts that are stacked in fuel holes of hexagonal-shaped nuclear-grade graphite blocks 0.8 m height and 0.36 m across flats size. The design of these fuel blocks is the same as proven in the Fort Saint Vrain (USA) demonstration plant. The standard fuel block contains about 20 million coated fuel particles; only 0.7 kg of Pu is loaded per 115 kg mass of graphite fuel block. The core fuel blocks have burnable poison compacts on the basis of natural erbium (Er_2O_3). Erbium oxide particles are coated by high density pyrocarbon and silicon carbide as fuel particles. The absorber performs two functions: compensation of reactivity margin during reactor operation between refuelings and ensuring the negative value of the reactivity temperature coefficient. Erbium contains ∼23% of Er-167 which has a pronounced resonance (almost 10^4 barn) at the neutron energy about 0.5 eV, and blocks the neutron capture by Pu-239 at the decrease of temperature. Burnable poison compacts and fuel compacts have the same design and dimensions.

The annular type reactor active core (Fig. 2) is composed of hexagonal graphite fuel blocks arranged in 102 columns, each 10 blocks high. Each fuel block has 202 channels for fuel compacts (15 fuel compacts per channel through its height), 108 channels for coolant and 14 channels for Er_2O_3 burnable poison compacts (15 burnable poison compacts per channel through its height). These channels are arranged in the triangular lattice with 19 mm pitch. The channels for scram absorber rods of 130 mm diameter are arranged in 12 fuel columns of the first internal row of the core. The channels for the reserve shutdown system (RSS) to be filled, if necessary, by small B_4C absorber balls under accidents are placed in 18 fuel columns of the second and third internal rows of the core. The annular fuel assembly stack (core array) is surrounded by the inner, outer, upper and lower replaceable reflectors.

The replaceable reflector is built up from 163 columns, each 13 blocks high. There are 102 columns in the side replaceable reflector and 61 columns in the inner one. The upper and lower reflectors are arranged above and below of the fuel assembly stack, respectively. Blocks in 36 columns of the side reflector have channels for control rods. All control rods

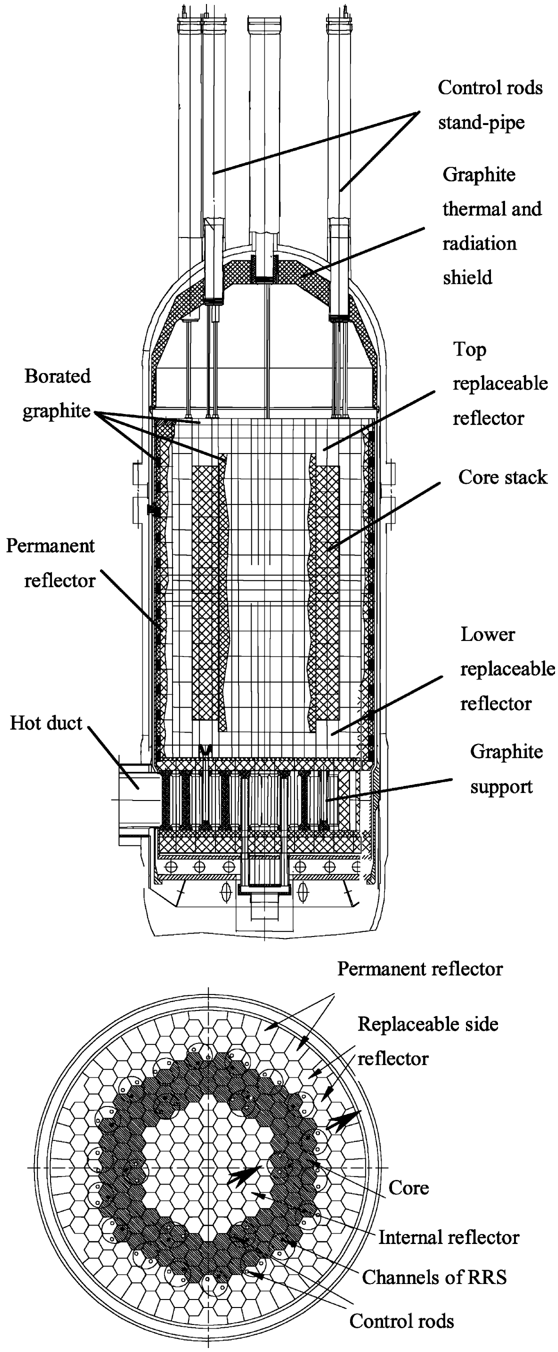

Fig. 2. Reactor core arrangement.

Table 1
Basic design parameters of the reactor plant (Kodochigov, 2000)

Performance	Value
Full thermal reactor power, MWt	600
Inlet helium temperature, °C	490
Outlet helium temperature, °C	850
Core geometric parameters:	
Equivalent core diameter, inner/outer, m	2.96/4.84
Core height, m	8.00
Average core specific power, MW/m^3	6.50
Number of fuel blocks	1020
Prismatic fuel block geometrical parameters:	
Height, m	0.80
Size across the flats, m	0.36
Number of fuel compacts per fuel block (in core average)	2862
Fuel temperature limit, °C	≤1600[a]
Number of reactivity control rods	
In core	12
In side reflector	36
Number of reserve shutdown system channels	18
Allocated operative reactivity margin on control rods, % $\Delta k/k$	5.0
Xe-decay at transient from 100 to 15% of full power, % $\Delta k/k$	2.0

[a] Calculated value for plutonium fuel at high burnup (about 640 MW day/kg) when the limited fission products release has met.

as 12 in-core control rods can be used for scram. Control rods design does not consist of any metallic elements. The shell of B_4C absorber is graphite composite material so it is possible to use control rods at high temperature.

The main core design parameters are presented in Table 1.

3. Neutronic features of the GT-MHR

The GT-MHR reactor is characterized by the following specific features:

1. Use of the coated fuel particles in fuel blocks, that ensures for the GT-MHR reactor additional effective barriers to the release of radioactivity to the environment in contrast to other types of reactors. This fuel block structure results in the double heterogeneity of the fuel location in the core, which must be accounted for in the calculation of the neutronic characteristics.
2. Use of the pure Pu fuel without fertile materials such as U-238 or Th-232, that results in the deep fuel burnup and need to use burnable poison.
3. High working temperatures in the core, that can result in positive temperature effect of reactivity at the use of Pu fuel without fertile materials.
4. Use of erbium as burnable absorber in the reactor core to guarantee the negative value of the reactivity temperature coefficient and to minimize the reactivity change during burnup.
5. Use of the annular-type active core design to prevent fuel damage in accidents even with the failure of helium circulation, that results in the non-symmetric radial power distribution.
6. Location of operational control rods outside of the active core in the side reflectors.
7. Long core axial size versus its diameter ($H/D \approx 1.5$), that results in the noticeable non-uniformity of the axial power distribution.

All these neutronics features of the GT-MHR reactor have an essential influence on the basic reactor parameters and were accounted for the reactor design.

Some illustrations for these neutronic features are presented below.

Neutronic analysis of full reactor was carried out in the 3D diffusion approximation by JAR code (Yaroslavtseva, 1983). Neutron cross-section were prepared for different physical zones of the GT-MHR reactor by the WIMS-D/4 code (Askew, 1966). The last code also was used for cell burnup calculations.

The double heterogeneity of fuel arrangement in fuel blocks with Pu has a weak effect on the neutronic characteristics.

The multiplication coefficient in the reactor with plutonium fuel depends only slightly on the fuel particle parameters. The fuel composition in the GT-MHR is ‘weakly heterogeneous’ in comparison, for example, with HTGRs with low-enriched uranium fuel, where the variation of the fuel kernel diameter from 200 to 500 μm results in the variation of multiplication coefficient more than 3%.

The variation of the multiplication coefficient versus time is shown in Fig. 3.

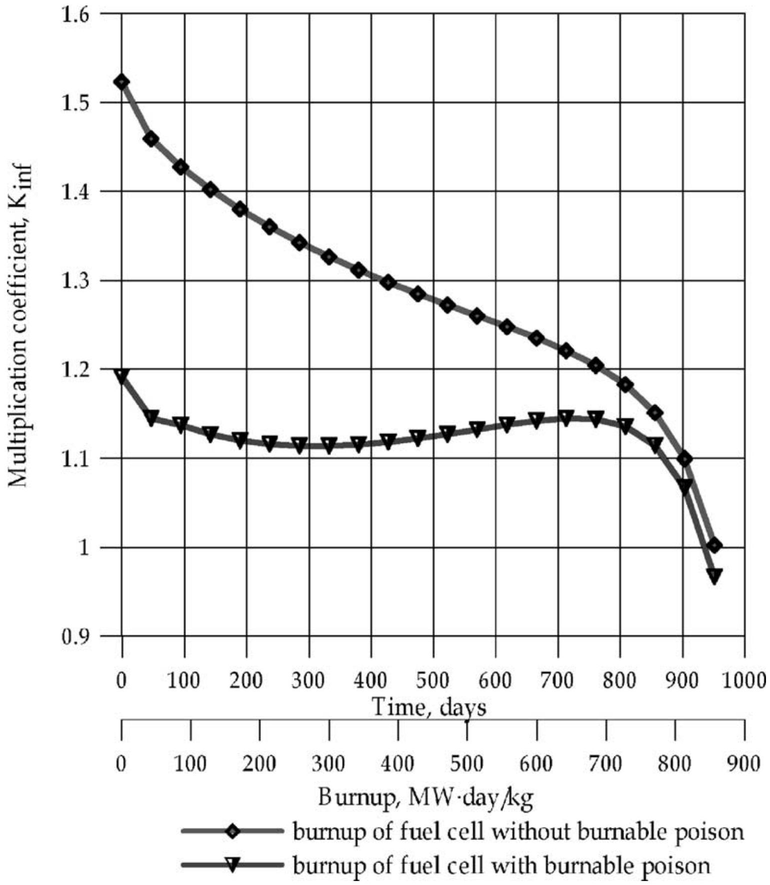

Fig. 3. K_{inf}, K_{eff} dependence vs. time.

The decrease of K_{inf} during burnup has a flatter character that is caused by the Pu-241 accumulation. Difference of K_{inf} for fuel cell with and without burnable poison shows the incomplete burnup of Er isotopes compared to Pu isotopes. This causes the sharp decrease of the multiplication coefficient at the end of fuel life. This incomplete burnup of Er leads to the loss of about 50 EFPDs in the fuel lifetime. The last fact is unfavorable from the viewpoint of fuel cycle economics, but presence of Er is necessary for the reactor fueled by pure Pu to ensure the negative temperature reactivity coefficient.

There is an essential non-uniformity in the power distribution at the core and internal reflector boundary for the annular-type core with Pu fuel. This fact is caused by accumulation of thermal neutrons in the reflectors, combined with a rather hard neutron spectrum in the active core and its relatively small thickness. The leakage of neutrons from the active core is significant.

Fig. 4 shows the power distribution in some chosen radial direction (see Fig. 2) obtained from reactor calculation in the fine-mesh approximation with all control rods withdrawn. The maximum value of peaking factor reaches ∼2.4 at the internal reflector/core boundary in the case without fuel and poison zoning. By reducing the Pu loading in five rows of fuel compacts adjacent to the internal reflector to 0.1 g Pu/compact (instead of 0.24 g Pu/compact in the rest of the core), the peaking factor can be reduced to 1.25. Practically the same result can be achieved at use of separately placed permanent boron rods in graphite blocks of the internal reflector adjacent to the core boundary (option of poisoned internal reflector).

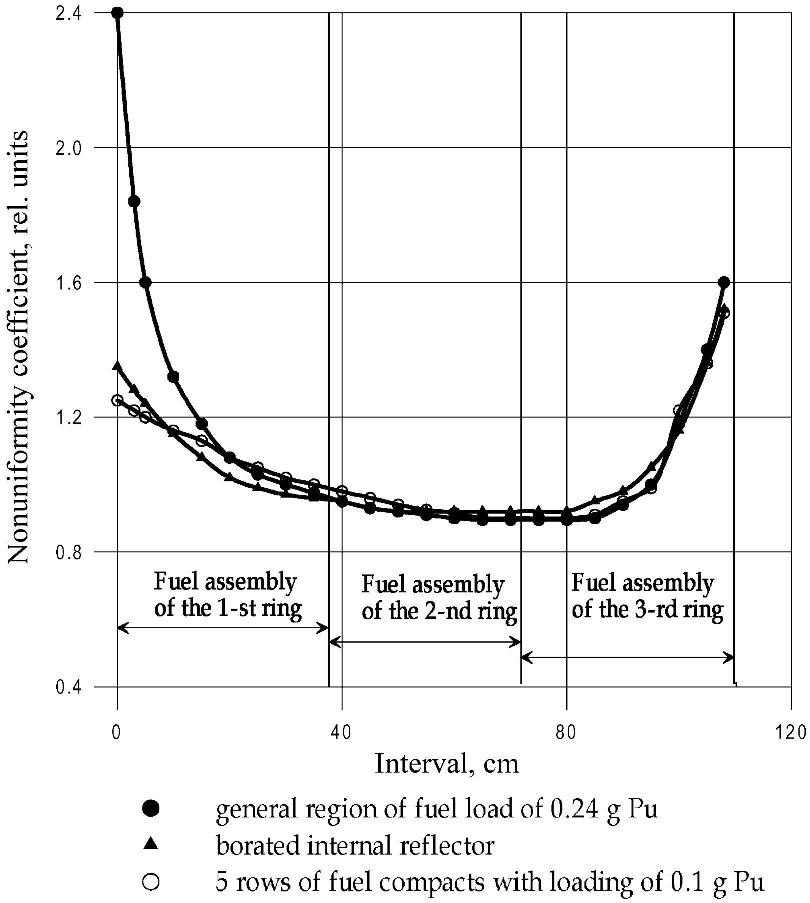

Fig. 4. Radial power distribution.

At the actual position of the control rods in the outside reflector, the peaking factor reaches 1.6 at the core/internal reflector boundary, and can be additionally reduced by the fuel and erbium poison zoning along the core radius. The typical radial and axial power distribution are shown in Figs. 5 and 6. Fig. 7 indicates the radial profile of core exit helium temperature.

To illustrate the effect of the core temperature on reactivity, the energy dependence of the neutron cross-sections for main isotopes in the core is shown in Fig. 8. In the GT-MHR active core the thermal neutron flux has its maximum at the energy of 0.1 eV. As shown in Fig. 8, with the increase of temperature, the Pu-239 fission cross-section increases from 450 barn at $T = 300$ K to 800 barn at $T = 1200$ K. This causes the positive reactivity temperature coefficient in a pure Pu fueled core. The influence of Pu-240 resonance, which competes with neutron capture in Pu-239, takes place at high temperatures (more than 1000 K). In the poisoned reactor (with Xe-135), the effect of multiplication coefficient increase is aggravated by the decrease in the Xe-135 cross-section.

To compensate for these effects in the reactor core with WGPu, it is necessary to use a poison with increasing capture cross-section at the energy range above 0.08 eV. Natural erbium containing 23% of Er-167, which has such a feature, is used in the GT-MHR reactor.

The presence of Er in the required amounts leads to the hardening of the neutron spectrum, additional

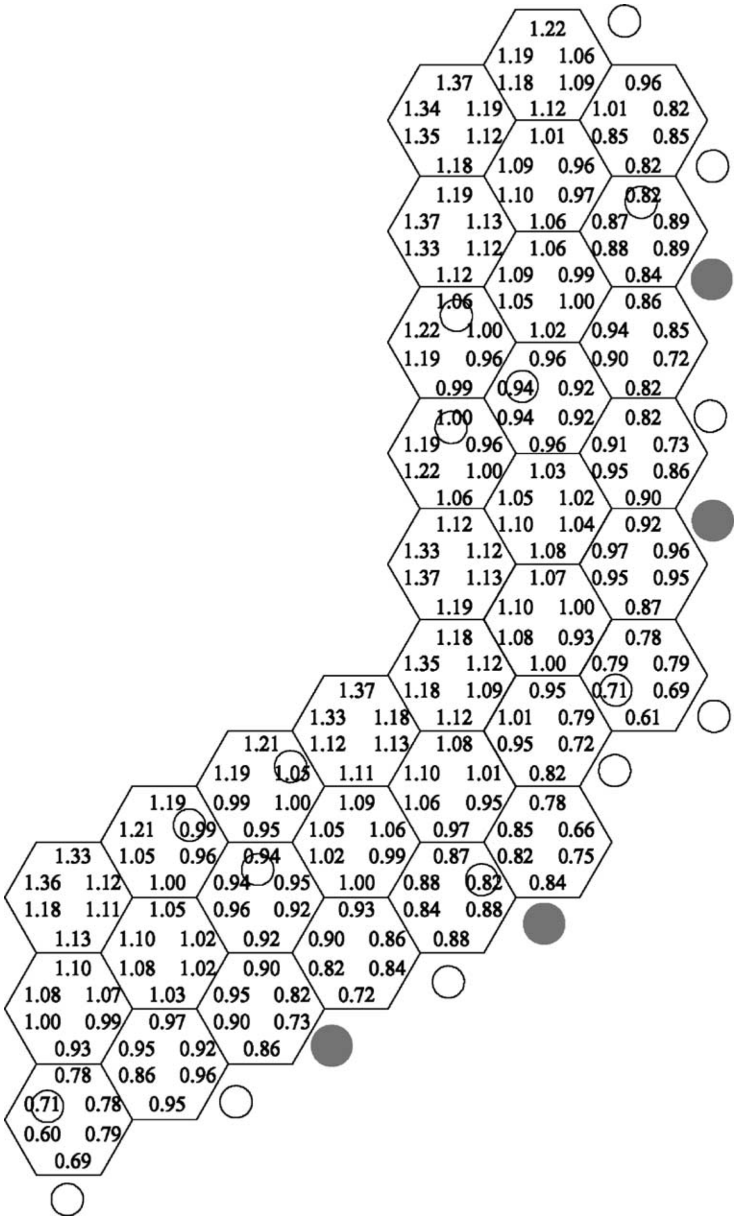

Fig. 5. Typical power distribution averaged by core height (1/3 core).

parasitic neutron capture, and increase in the fissile materials consumption.

The dependence of the reactivity temperature coefficient (both of fuel and moderator) on the temperature for the reactor poisoned by Xe at the beginning and the end of equilibrium burnup cycle is shown in Fig. 9.

These results were obtained for reactor with the three-batch fuel reloading scheme with fuel shuffling only in axial direction presented in Fig. 10.

The reactivity temperature coefficient for the state after refueling is obviously negative, but for the state before reloading there is the temperature range

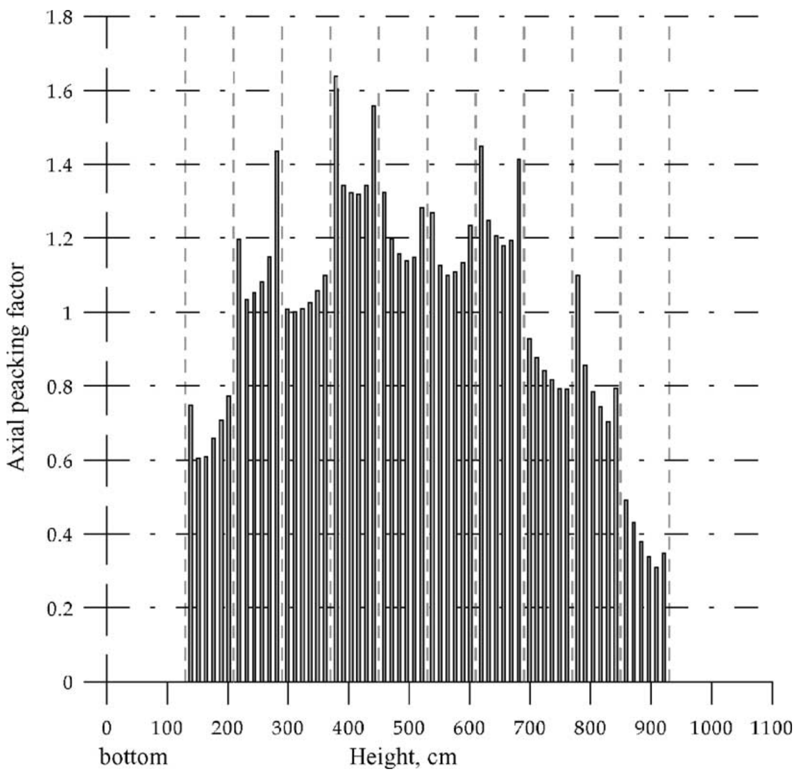

Fig. 6. Typical axial power distribution averaged by core radius.

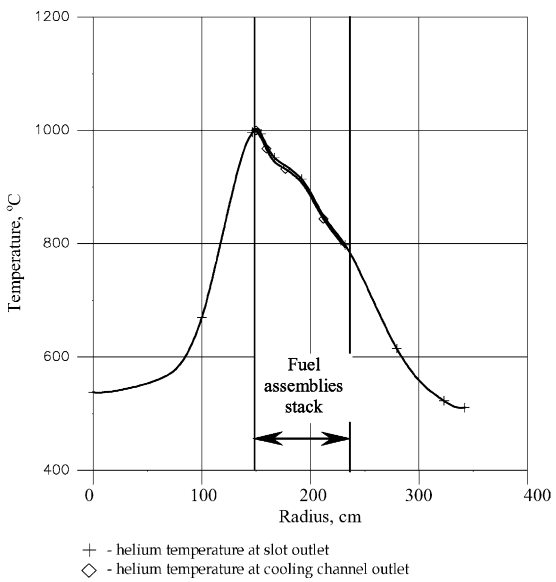

Fig. 7. Radial profile of core exist helium temperature.

(below 400 °C) where the reactivity temperature coefficient is close to zero. In the reactor without Xe poisoning the reactivity temperature coefficient is negative in the whole temperature range. The fact that reactivity temperature coefficient can be close to zero at reactor start up conditions does not prevent meeting the safety requirements because of a large temperature margin to fuel temperature limit 1600 °C. For instance, the fuel temperature in accident with group of control rods withdrawal at reactor start-up does not reach 1200 °C even in absence of SCRAM.

Because of the high burnup and absence of new plutonium accumulation, the GT-MHR consumes about 90% of initially charged Pu-239 or approximately 270 kg of WGPu per year in one reactor module. A single GT-MHR plant consisting of four reactor modules can achieve this level of Pu-239 destruction for 50 metric tons of WGPu in 46 years of operation with concurrent electricity generation

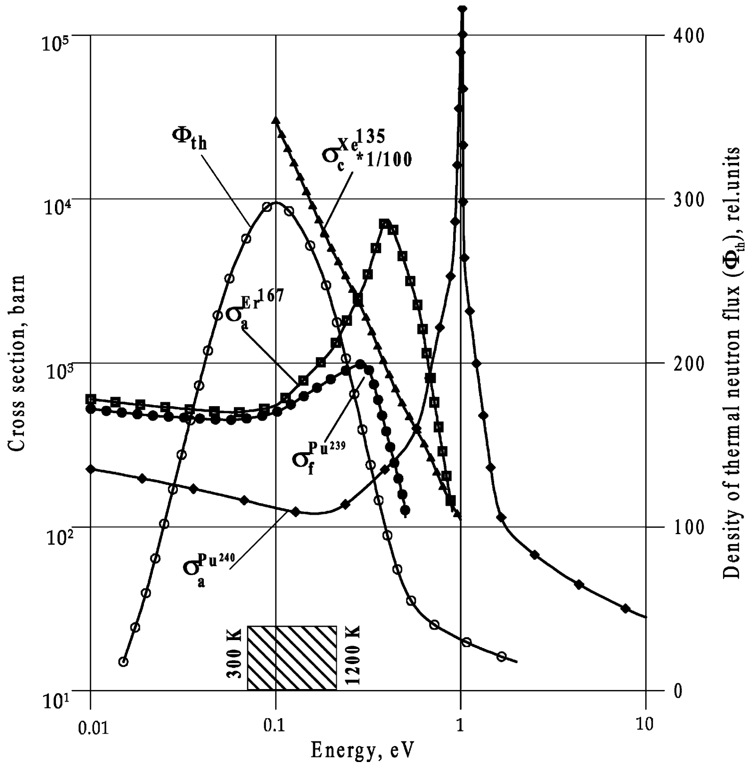

Fig. 8. The main isotopes cross-section.

of 42 GWe-year at the 0.8 capacity factor. In this evaluation it is assumed that the GT-MHR has three refuelings per the whole fuel cycle, fuel lifetime is 750 EFPDs, and the average burnup is 640 MW day/kg.

Table 2 illustrates the advantages of the GT-MHR for the WGPu disposition (without fuel recycling) in comparison with other types of reactors.

Plutonium of the spent fuel discharged from the GT-MHR after its single use in core contains about 30 wt.% of Pu-239 and about 30 wt.% of Pu-240 that makes such spent fuel unattractive for the reprocessing both for commercial or military use because Pu containing Pu-240 more than 10% is not considered as weapons, and, thus, effectively resolves the proliferation issue.

Table 2
Comparison of Pu disposition in reactors of different type (without fuel recycling)

Reactor characteristic	GT-MHR	VVER-1000 (with loading of MOX in1/3 core)	Fast sodium reactor BN-800
Thermal power, GW	0.6	3.0	2.1
Net efficiency, %	48	33	38
Annual WGPu consumption, t	0.27	0.27[a]	1.65[a]
Electricity generation at disposition of 50 t WGPu, GWe-year	42	47	19
Level of Pu-239 burning, %	90	63	17

[a] Joint U.S./Russian Plutonium Disposition Study (1996).

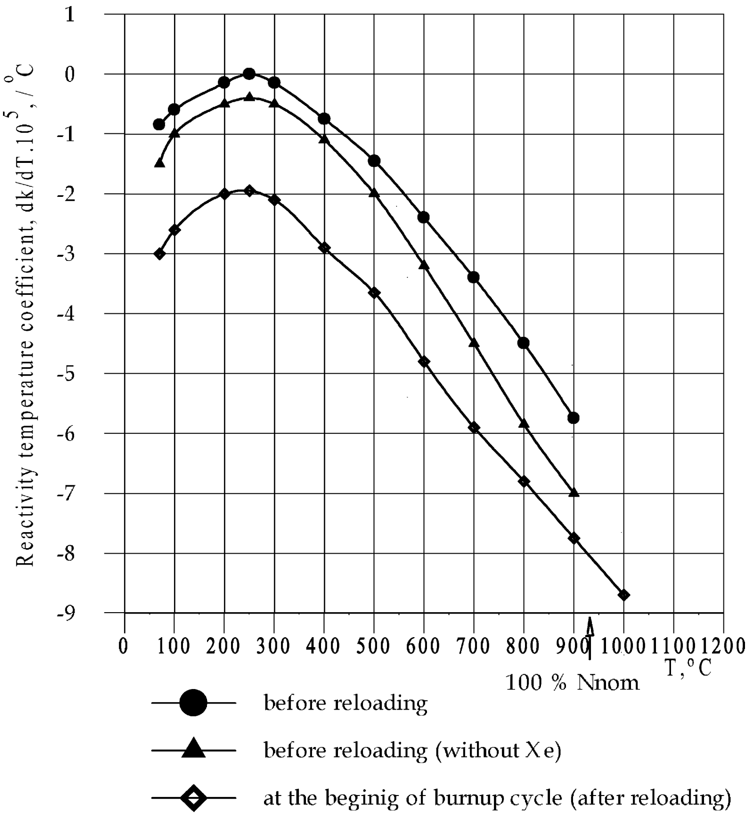

Fig. 9. Reactivity temperature coefficient.

	Number of fuel layer in axial direction										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
1 cycle →	**2/3**	**0**	**2/3**	**0**	**1/3**	**1/3**	**0**	**2/3**	**0**	**2/3**	
	(3/3)	**1/3**	**(3/3)**	**1/3**	**2/3**	**2/3**	**1/3**	**(3/3)**	**1/3**	**(3/3)**	before → reloading
2 cycle →	**2/3**	**0**	**1/3**	**0**	**1/3**	**1/3**	**0**	**1/3**	**0**	**2/3**	
	(3/3)	**1/3**	**2/3**	**1/3**	**2/3**	**2/3**	**1/3**	**2/3**	**1/3**	**(3/3)**	before → reloading
3 cycle →	**2/3**	**0**	**2/3**	**1/3**	**1/3**	**1/3**	**1/3**	**2/3**	**0**	**2/3**	
	(3/3)	**1/3**	**(3/3)**	**2/3**	**2/3**	**2/3**	**2/3**	**(3/3)**	**1/3**	**(3/3)**	before → reloading

0 - fresh fuel;

1/3 - fuel blocks with 1/3 burnup level (exposed during 1/3 of their design life);

2/3 - fuel blocks with 2/3 burnup level;

3/3 - fuel blocks with 3/3 burnup level.

Fig. 10. Fuel reloading scheme.

4. Conclusions

The fundamentals of the WGPu disposition in the GT-MHR, as a high temperature gas cooled reactor, are the following:

1. Efficient plutonium burning at its single use in core, and concurrent electricity generation.
2. Use of WGPu in the form of coated fuel particles with multi-layer ceramic coatings, resulting in the high burnup (640 MW day/kg on average through the core), and eliminating the need for the processing of the spent fuel before its final disposal in the form of whole fuel elements. This is the more effective option of WGPu utilization than vitrification or any other option of WGPu disposition in reactors without fuel recycling.

The physics characteristics of the GT-MHR reactor with WGPu (high fuel burnup, essential non-uniformity of power distribution in the annular core, complicated dependence of the temperature reactivity coefficient versus isotope content) require comprehensive calculational and experimental justification.

To qualify the design characteristics, it is expected to perform the experimental simulation of annular core configurations at the Russian critical facilities. The goals of these experiments are to study the power distribution and the possibility of its flattening, to investigate control rod worth in the side reflector and in the active core, to study the effect of rod position on core neutronic characteristics, etc. Benchmark calculations of the initial loading of the HTTR reactor (Japan) could contribute to the resolution of these problems, too.

For the verification of calculational methods of Pu fuel burnup in the reactor, it is necessary to carry out the benchmark calculations and experiments addressing the high burnup of Pu fuel compacts in reactor conditions close to actual ones in the GT-MHR reactor.

Acknowledgements

The authors express their gratefulness to G.N. Binder for review and useful discussion on this paper.

References

Askew, J.R., et al., 1966. A general description of the lattice code WIMS. JBWES, p. 564

Joint U.S./Russian Plutonium Disposition Study, 1996. Prepared by the Joint U.S.-Russian Plutonium Disposition Steering Committee. U.S. Department of Energy (http://plutonium-erl.actx.edu/jointusrusspds.html).

Kiryushin, A.I., Ponomarev-Stepnoy, N.N., et al., 1997. The project of the GT-MHR high-temperature helium reactor with gas turbine. Nucl. Eng. Design 173, 119–129.

Kiryushin, A.I., Ponomarev-Stepnoy, N.N., et al., 1998. Burning of weapons-grade plutonium in the gas-turbine modular helium reactor, Col. “Questions of Atomic Science and Technique”, Ser. “Physics of Nuclear Reactors”, Moscow (in Russian).

Kodochigov, N.G., et al., 2000. Analysis of different fuel cycles for GT-MHR. IAEA IWGGCR Meeting, Vienna, Austria.

Ponomarev-Stepnoy, N.N., 2000. Plutonium—man-made fuel of the 21st century. In: Proceedings of the International Conference “Plutonium Futures—The Science”. Santa Fe, New Mexico, USA.

Yaroslavtseva, L.N., 1983. JAR: complex of codes for calculation of neutron-physical characteristics of nuclear reactors, Col. “Questions of Atomic Science and Technique”, Ser. “Physics of Nuclear Reactors”, Moscow, vol. 8, no. 37, p. 41 (in Russian).